AIR CONDITIONER USER BEHAVIOR IN A MASTER-METERED APARTMENT BUILDING

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ABSTRACT

Air conditioner operation was studied in order to understand how energy consumption and peak power are determined by user behavior, equipment operation and building characteristics. In a multi-family building, thirteen room air conditioners were instrumented in eight apartments, and interviews were conducted with the residents about their operation of the units. The predominant mode of operation was to switch the unit on and off manually; only one resident consistently let it operate thermostatically, and many residents were not aware that the unit had a thermostat. Ambient temperature and time of day were observed to have major effects on the occupant's decision to turn the unit on or off. Even though residents did not pay for electricity, numerous noneconomic factors were found to limit their use of air conditioning. Across apartments, seasonal air conditioner energy consumption varies by two orders of magnitude while interior July temperature varies by 3.7°C.

INTRODUCTION

This paper reports an intensive field study of the determinants of residential air conditioner energy use. Air conditioning accounts for a significant fraction of electrical energy use, and determines the peak load in most parts of the country. We believe that a better understanding of the physical and behavioral determinants of air conditioner load will help in planning and evaluating conservation or load control strategies such as peak pricing, direct load control, and rebates for handing in inefficient units.

Our study includes a strong behavioral component in addition to the environmental, building and equipment variables. We include this aspect based on evidence from several studies that behavior is a major, perhaps the largest, component of variation in air conditioner energy use. Experimental work by Seligman, Darley and Becker (1978:249) showed that a 15 percent savings in electricity consumption was possible by changing only one component of behavior: residents were promoted to turn off the air conditioner and open windows by a device indicating that it was cool outside. A second study by Winett et al (1982) was designed to affect a broader range of air conditioner behavior through information and minor incentives. This study achieved a 34% reduction in air conditioner energy use, with no change in perceived comfort or clothing worn, and with minimal temperature change in the home.

A less direct type of evidence derives from a comparison of modelled with measured seasonal air conditioner energy consumption in occupied residences (McLain et al 1985). The modelled energy consumption exceeded the measured values by as much as 60 percent until the model was augmented to include resident behavior. We hypothesized that a field study documenting the environmental and behavioral determinants of air conditioner energy consumption would provide a firmer basis for future work on air conditioner use, whether theoretical modelling, experiments attempting to improve efficient operation, or utilty load control programs.

In order to understand the behavioral component, we have tried to determine the factors which influence how residents set the controls of room air conditioners, and the consequent effects of those settings on energy use. This entailed interviewing the residents and comparing the interview data with electronically collected records of operation of their air conditioners. These data were compared with our measurements of environmental factors such as external temperature, relative humidity and solar radiation.

THE STUDY

The research has been conducted in situ rather than in the lab, to determine what factors are at work with occupied buildings. We have picked a 62-apartment building in our area (central New Jersey) occupied by middle-income tennants, mostly adults living without children, with a mix of white Anglos and blacks. In this building, electricity is centrally metered and residents are not directly billed either for electricity or for the purchase and maintaintenance of the apartment's window air conditioners. Because we find that residents report a great many noneconomic factors limiting air conditioner use, this building was a good starting point for our research. Had we interviewed metered residents, we might have dismissed reported noneconomic limits as after-the-fact rationalizations for cost savings.

Our instruments measured outdoor temperature, relative humidity, solar global horizontal radiation, and total electricity consumption for the building. In eight individual apartments, for 13 air conditioner units, our sensors measured compressor runtime and temperature in each room with an air conditioner. For three air conditioner units power was also measured. All units (window air conditioners) were rated at eight to nine thousand BTU/hour (2.3 to 3 kW_{th}). The units typically drew about 1.1 kW when the compressor was running, so the nominal COP is about 2.4. We inspected several of the units and took two to our lab for testing. Nominally, the smaller apartments had one air conditioner and larger apartments had two (one in the bedroom and one in the living room), but a number of the units were nonfunctional and produced no operating data. Our

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sensors in the apartments were connected via a digital power-line carrier to a transceiver and personal computer in the basement which sampled each sensor every 15 seconds and recorded a sum or average each hour.

Our data show that the user control of these units is a crucial determinant of the device operating characteristics. We illustrate this point first by two graphs plotting hourly compressor runtime (in fractions of an hour) against outside temperature (°C). Figure 1 shows a unit in an unoccupied apartment when we left the thermostat on a constant setting. Outdoor temperature strongly determines compressor runtime (the Pearson correlation was r=.80). This linear relationship with temperature is expected, given the physics of the device and the apartment's heat gain.[1]

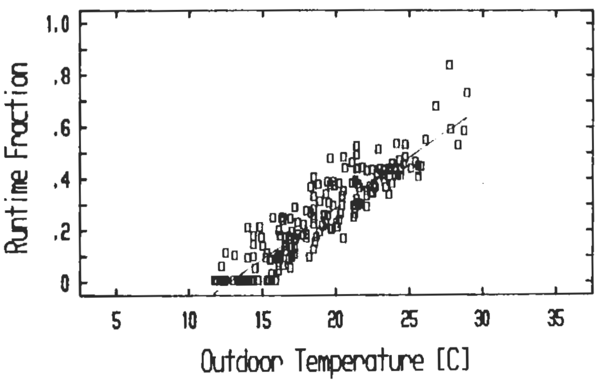

Figure 1. Hourly compressor runtime fraction against outdoor temperature, unoccupied apartment 4C with thermostat at moderate setting.

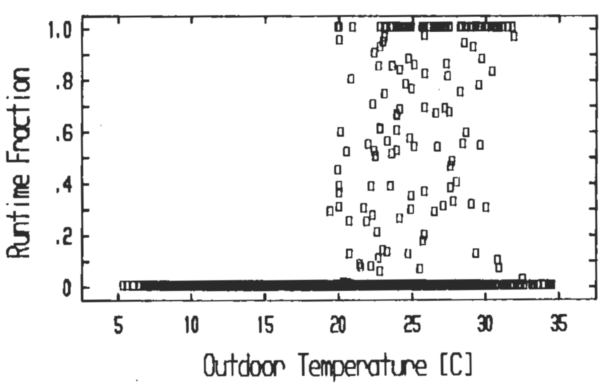

Figure 2. Hourly compressor runtime fraction against outdoor temperature, occupied apartment 4C.

In an occupied apartment one might also expect the compressor runtime to be linear with temperature, but more scattered due added random behavioral "noise". However, Figure 2 (from the same air conditioner when this apartment was occupied) shows a distinctly different pattern created by a new control device added to the system--the human user. At any temperature, the unit may be off. There is a threshold at 20°C (68°F) below which it is not switched on. Most hourly points are either at off for the entire hour or on the entire hour, and many of the partial hour points represent transition from one to the other. The point of comparing these two figures is to argue that one cannot simply study room air conditioners in the lab or in unoccupied apartments if the goal is to understand actual field operation or the determinants of energy and peak load. Much of this paper will attempt to explain the seemingly random pattern of Figure 2 and its implications for summer electric loads.

SAMPLING

This building was instrumented to serve several projects, and our sampling of apartments was partially opportunistic.[2] Nevertheless, we have no reason to expect that sampling is biased on the variable of interest--air conditioner loads. Figure 3 is a plot of the daily average load of the aggregated instrumented air conditioner units against the load of the entire building for June through September 1986. The building's daily average peak of just over 70 kW is dominated by air conditioning, with the intercept on the graph indicating the base (non-air conditioning) load at only 20 to 25 kW. While our small sample shows a lot of scatter, the relationship appears to be linear rather than curvilinear, and the correlation is strong (r=.81), suggesting that the operating characteristics of the sampled units match those of the building as a whole.

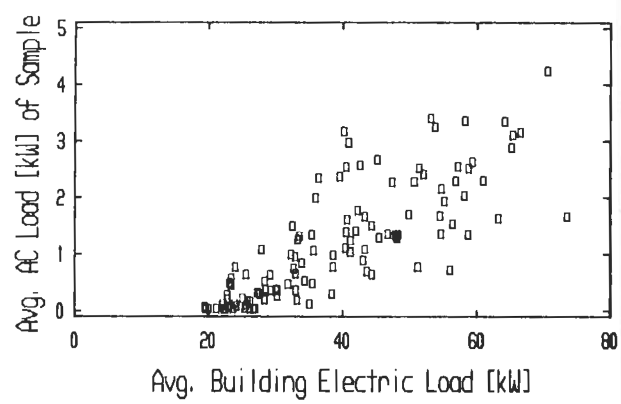

Figure 3. Total load of building against average air conditioner load of the eight sampled apartment.

THE DEVICE

The window air conditioners all had the same control capabilities: 1) a switch controlling fan speed and whether the unit was on or off, 2) a thermostatic control which switches the compressor on and off based on the room temperature, 3) a lever which opens a duct to the outside (drawing part of the air from the outside) and 4) a moveable deflector which directs the stream of cold air within the room. When the unit is on, the fan runs constantly and the compressor switches on and off thermostatically. The thermostat is labelled "cooler" and marked with an arbitrary 1 to 10 scale; the setpoint is not marked in temperature units. There is no thermometer for the interior temperature, nor is there an indicator for whether the compressor is running or not. The only indicators of operation are the sound of the fan and compressor and the feel of the moving air. The compressor sound is barely distinguishable under the

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fan noise; since the fan runs continuously, thermostatic operation of the compressor is not at all obvious.

INTERVIEWS

Our interviewing used ethnographic techniques in order to better understand user operating practices and conceptions of the device. We began with a list of 32 questions we made sure that the intervierw covered, but following ethnographic procedures we let the informant add to the agenda and partially determine the interview sequence. We asked additional follow-up questions on topics the informant seemed to consider significant, even if they were not anticipated by our questions. The questions were based on prior studies of cooling by Hackett et al (1984), Diamond (personal communication), and on Kempton's earlier findings of erroneous device models for heating thermostats (1987). Some interviews were conducted about six weeks into the cooling season, the rest at the end of the cooling season.

In outline, the interview was conducted as follows. The initial part of the interview covered basic household demographics and asked how many working air conditioners they had and who operates them. (We did not continue the interview if we were not speaking with the primary operator of the air conditioner in that household.)

The second part of the interview focused on the user's operation of the controls. We asked the interviewee to stand by the air conditioner and show us how they operated it. We also asked what they thought the controls did and asked about any additional controls they had not mentioned. We believe this technique improves the respondent's recall and helps insure that we understand their descriptions of equipment operation.

The next part of the interview covered when and why they would turn on the air conditioner. Questions asked about the factors influencing the informant's decision to use it (temperature, humidity, time of day, household activity, noise, health, or a desire to dry out the apartment), how they would decide between using the air conditioner versus opening windows, using a fan, or changing to lighter clothing. We asked about differences in air conditioning preference among people within their household, whether the household in which they grew up had an air conditioner, how they thought their own use compared with other people in the building, and why they thought some people use the air conditioner more than others. We also asked informants to estimate the number of hours they use their air conditioner and what it would cost if they were being billed for it. Finally, we asked whether they did anything to maintain the unit. These interviews helped to correct our initial simplified stereotype of how people use air conditioners. We had previously assumed that people turn on air conditioners when they feel hot and set a temperature at which they will be comfortable. We thought that most people limit use primarily because of cost, and thus in our study building where electricity is not billed we expected people to operate their air conditioners primarily on the basis of comfort. However, we instead we find a multitude of noneconomic factors which limit air conditioner use. We find that operation is rarely thermostatic, and that use is governed by household schedules and by multiple systems of belief and preference concerning health, thermal comfort, alternative cooling strategies, theories about how air conditioners function, and general strategies for dealing with machines.

<u>Comparison of Individual Usage Patterns</u>. We illustrate individual usage patterns of the living room air conditioners first with a graph of two days, then a compressed graph to illustrate the entire cooling season. Usage patterns are described with the variable "runtime fraction", defined as the fraction of an hour during which the compressor was

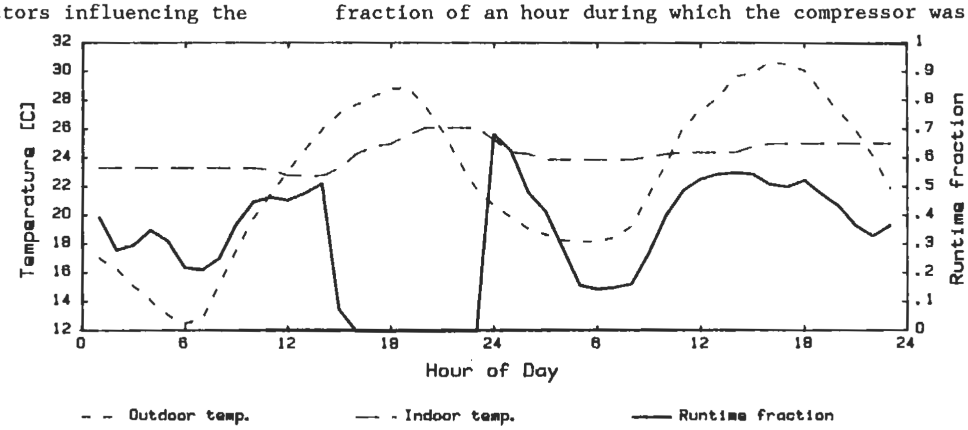

Figure 4. Apartment 2K living room for two days of hourly data: outdoor temperature (dotted line), indoor temperature (dashed line), and compressor runtime fraction (bold line). A thermostatic usage pattern.

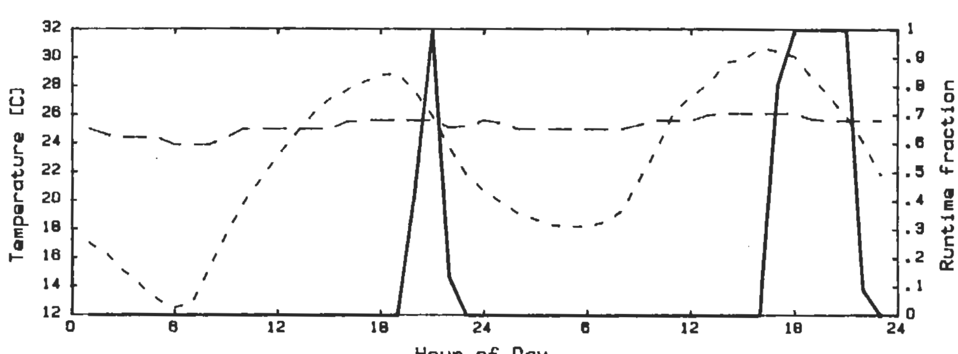

Figure 5. Apartment 2M living room for the same two days as shown in Figure 4, an on-off switching pattern.

running. The runtime fraction of an hour may be less than one either because the occupant switched the air conditioner on or off partway through the hour, or because the thermostat was switching the compressor on and off automatically.

Figure 4 shows interior and exterior temperature and air conditioner operation in apartment 2K over a two-day period. The air conditioner runtime fraction (dark line) normally varies between 0.1 and 0.8, with one eight-hour period when it is turned off (so the runtime fraction is 0.0). During the period of air conditioner operation, the interior temperature is fairly constant, but it climbs several degrees when the air conditioner is off. This is a clear pattern of thermostatic operation.

By contrast, Figure 5 shows compressor runtimes of either zero or 1.0, with the fractional values occurring only in transition, when the unit has been turned on or off part way through the hour. The operation of the compressor does not correspond to temperature rises but rather to the evening hours. We infer that the resident is switching the air conditioner on manually. Inspection of plots for other days in apartment 2K shows that the compressor will run continuously even after the interior temperature drops several degrees, suggesting that the resident sets the thermostat to such a low temperature that thermostatic cutoff is unlikely before she manually turns the unit off. Finally, we note little change in interior temperature, even without the air conditioner.

A more complete picture of air conditioner operation is seen in Figure 6. These graphs include the entire cooling season (115 days from early June through September). Exterior temperature is shown in Figure 6.A. Days can be distinguished by the diurnal cycle, with one maximum for each day (gaps indicate occasional missing data). The other three plots represent fractional runtime for each hour of the summer, totalling 2,760 hours for each apartment. The two-day span of figures 4 and 5 is noted by brackets in the corresponding apartments. Even on this whole-season graph, the eight-hour off period in apartment 2K and the different lengths of on-periods in apartment 2M can be distinguished. We next discuss the individual apartments in more detail.

In apartment 2K (Figure 6.B), we see that for most of the summer when the air conditioner is run, it runs for only fractions of an hour. As in the two-day graph, we infer thermostatic switching. This is consistent with the resident's interview data. The resident is often home during the day, working on maintenance of the building, and reports leaving it on continuously when he is "going in and out."

In contrast, the graph for apartment 2M (Figure 6.C) does not show a pattern of thermostatic control. Rather, the unit is switched on, it runs continuously, and it is then switched off. Thus the pattern seen for two days in Figure 5 extends throughout the season. Again, the pattern indicated by the instruments is explained by the interview data. The occupant reports turning it on when she comes home

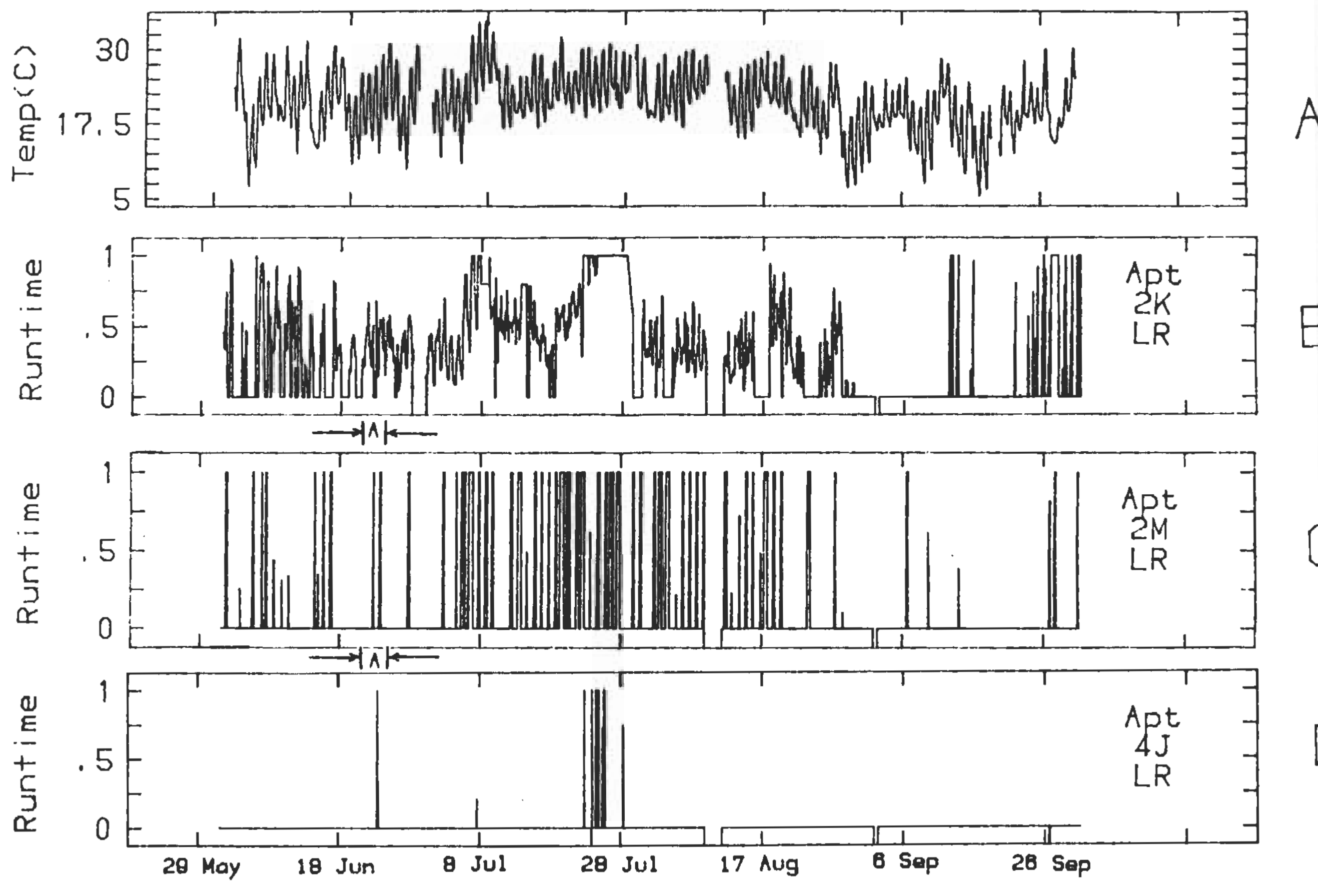

Figure 6. Entire cooling season: A) Outdoor temperature, B) Runtime fraction for apartment 2K, a thermostatic pattern, C) Apartment 2M, an on-off pattern, D) Apartment 4J, an infrequent user with an on-off pattern. The scale of days is marked in twenty-day intervals; the bracketed A indicates the two days expanded in Figures 4 and 5.

from work, then turning it off either if it bothers her while watching television (cold/air blowing and noise) or when she goes to sleep. She says the apartment is cool enough when she goes to sleep. She has problems with arthritis, and since she has air conditioning all day at work, she doesn't want it all night as well. She said that she assumes that if the air conditioner "is working ok," she should leave the thermostat as it is; she says she has not touched "that knob" (the thermostat) since moving in earlier this year. We observed that the thermostat was at a very high (cold) setting. Although the mechanical thermostat on the unit is not cycling, comparison of apartment 2M's use with the outdoor temperature suggests that she is more likely to turn on the unit during hot periods than during mild ones; thus the user is providing a partially thermostatic control.

Finally, apartment 4J (Fig. 6.D) shows a non-thermostatic on-off pattern like that of apartment 2M, but with much lower frequency. In the interview, the resident of 4J said, "I'm not one for using the air condtioner" and "I'm not an air conditioner person", but the resident said that if it is "really hot and muggy" she might use it briefly to cool down the apartment. More than the other two, she is aware of ambient conditions and uses alternative cooling strategies. She leaves two windows open all day, and keeps all windows open when she's home. She attributes heating up of the apartment while she is away to solar gain through a sliding glass door. Her previous residence was on the 15th floor and had a "good breeze", and she reported never using the air conditioner the whole time she lived there. Her low usage--the lowest in the sample--makes sense given her awareness of environmental inputs and her willingness and ability to exploit natural ventilation for cooling.

Although the thermostatic pattern in apartment 2K would be expected from the design of the device, this is the only resident we monitored who ran the air conditioner thermostatically over any significant period of time. Apartment 1B uses thermostatic control only early in the summer, and 3A mixes thermostatic and on-off control. The other five apartments show a totally on-off control pattern like that of 2M or 4J, with frequency of use ranging between the two.

How do we know these different patterns are due to control by the occupant rather than a faulty thermostat or orientation of the apartment? We performed some experiments in an apartment which was vacated during the study period, shown in Figure 7. The first twenty days show the on-off pattern while the resident was still there. From 10 July to 21 July, we set the thermostat at an extreme high position and left it on. With one exception corresponding to a low outside temperature, the compressor ran continuously throughout the period. Then from 11 August to 22 August, we set the thermostat to an intermediate position. As seen in the graph, it switched on and off thermostatically, roughly in proportion to outside temperature. Finally, we set it at a lower setting from 22 August to 15 September, and it switched on only occasionally on the hottest days, never for more than 1/2 hour at a time. Since these four operational patterns are seen with the same device in the same apartment, the on-off pattern is clearly due to operator control.

Another indication that the patterns in Figure 6 are behavioral, not due to apartment orientation or equipment, is seen by a change of occupants in apartment 2K. The transition date is between the end of thermostatic operation on 30 August and the beginning of on-off operation about 10 September. As in our experiment, this is the same apartment and the same air conditioner; the change in pattern is caused by a different user.

The operating characteristics of the studied air conditioners are summarized in Table I. For the season, total hours in use ranges from 2.5 to 1557 hours and total energy consumed per unit ranges from 1.2 kWh to 1048 kWh. The duration of each use in column 5 shows a predominant pattern of leaving the unit on just 2 to 4 hours. By dividing compressor run time by total opearating hours, we obtain the fractional compressor run time. This fraction is .53 for the thermostatic operation of the living room unit in 2K, and .97 for the on-off operation of the living room unit of 2M. We believe that this quantity can be used as a simple metric of the user's operating mode.

Another measure of interest in Table I is the average room temperature for July, the hottest month of the cooling season. We use a probe in the room where the air conditioner is located, and average temperature data only from 6-10 pm, a time when the apartments are most likely to be occupied. The two to three orders of magnitude difference in energy

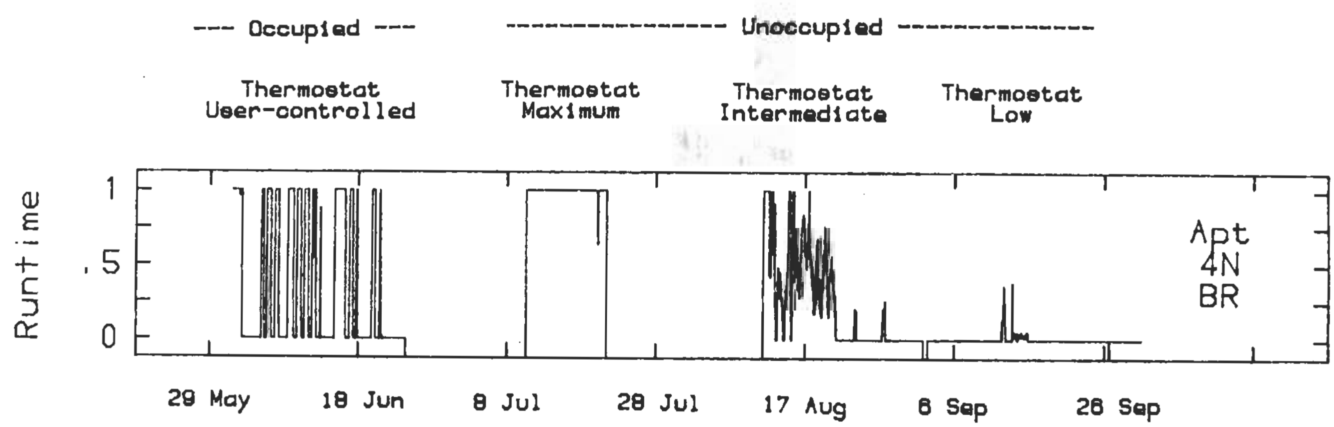

Figure 7. Different patterns obtained with the bedroom unit in apartment 4N. The leftmost pattern is that of the original occupant, the right three patterns were set experimentally by the researchers.

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Table I. Summary of measurements of room air conditioner use, with units ranked by energy consumption.

Unit	1 Days monitored (days)	2 Total hours in use (hours)	3 Total compressor run time (hours)	4 Total energy consumed (kWh)	5 Average duration per use (hours)	6 Fractional compressor run time (col#3/col#2)	7 Average July temperature indoors 6 pm-10 pm	8 Comfort temp. steady state operation (deg. C)
2k LR[1]	115	1557	818	1048	23.0	.53	24.9	24.3 ± 1.0
3a BR	115	475	358	417	3.2	.75	25.4	24.2 ± 0.9
2m LR	115	326	316	350	4.5	.97	26.2	(25.4 ± 1.1)[2]
3a LR	115	224	186	212	1.9	.83	25.7	24.3 ± 1.3
2k BR	115	251	165	199	8.9	.66	24.6	22.2 ± 1.1
4c BR	105	129	110	137[3]	4.0	.86	28.2	27.0 ± 1.3
1b LR	107	122	75	99[3]	2.8	.61	27.3	26.2 ± 0.5
4j LR	115	21	19.5	22	2.1	.95	28.6	(28.0 ± 1.0)[2]
4j BR	115	2.5	0.77	1.2	0.8	.31	28.6	(28.0 ± 1.0)[2]
Incomplete data:								
4g EF	73	145	133	149	2.7	.92		28.4 ± 0.6
4n LR	28	83	80	89	4.3	.97		25.3 ± 0.4
4c LR	57	32	31	34	10.7	.97		(24.5 ± 0.9)[2]

1 LR, BR, and EF stand for living room, bedroom, and efficiency, respectively.
2 This unit was used almost always at highest thermostat setting - if there is a steady state, it is purely behavioral.
3 Energy units have been scaled up to 115 days.

use[3] corresponds to a 3.7°C (6.7° F) difference in internal temperature. (The temperature difference is only 2.4°C when the whole summer is averaged.) The higher use of apartment 2K cannot be attributed to obvious physical differences since it is on a mid-floor, on the north side of the building.

USER DEVICE MODEL

The interviews validate and help explain the instrument data by showing that the predominant mode of air conditioner control is to use only its off/low/high switch. Five of the eight apartments reported no thermostatic use in response to our questions; in the remaining three apartments, we could not determine from the interviews whether the air conditioner was used thermostatically or not. Most of them referred to the thermostat as "this knob" or "the cooler knob" (we will call it a thermostat for clarity in this discussion). Three residents reported leaving the thermostat set at the maximum all the time, two of whom had problems with ice forming on the evaporator coils. One (4N) dealt with freeze-up by putting a towel under the air conditioner, turning it off until the ice melted, and turning it back on. Another (2K) was not aware of the freeze up but said: "I always turn it on super" with the thermostat on 9 (of 10) because "It doesn't run real great anyhow." Our inspection showed air blowing from only 20-25% of the vent area -- it wasn't running well because it was iced up.

We suspect that we would have found maximally cold thermostat settings in more of the apartments. However, the building superintendent found out about the freeze-up problem after we had conducted interviews with only three informants (two of whom set it full). Subsequently, the superintendent told a number of the residents not to set the thermostat at the coldest position, and we found it on a moderate setting in all subsequent interviews.

Two interviewees used the thermostat as a "gradual turn on" knob (4G, 4C). For example, 4G reported using the following procedure: Turn the thermostat fully down, run the air conditioner one minute on fan only, slowly turn the thermostat until the compressor comes on (position 5 or 6) then turn it up to 7. He said: "I turn the knob slowly until it gets to the air conditioner part--the fuses blow if I'm not careful" (4G). Several of the units burned out fuses regularly, so this particular use of the thermostat may be more prevalent in our study building than elsewhere.

Apart from the two occupants who used the thermostat to gradually turn on the air conditioner, none of the eight apartments reported using the thermostat at all. Three always left it on the maximum, as mentioned previously (2K, 2M, 4N). The remaining three said they did not use the thermostat knob (3A, 4J, 1B), two of whom said the manager had set it at an intermediate position and told them not to change it (1B, 4J). Many seem to think of the thermostat as a volume control or flow control, rather than as a thermostat.[4] The clearest case of this is a man (4G) who regulated the temperature by turning it the switch on and off. He said he would like to have an air conditioner you could turn on and set to a mild temperature, knowing it will get cool and then have it cut off automatically like heaters do. He also described the available controls on the air conditioner as being adjustments only "for the moment, not while you're away". In short, he knows how thermostats work and wants one on his air conditioner, not knowing that there is one already. Unclear panel design leads him to think the thermostat is only a rate control, so he is left to use his perceived body temperature and the air conditioner's on-off switch as a manual "thermostat."

Non-economic limits. We found surprisingly many noneconomic factors limiting air conditioner use. Two residents mentioned health reasons such as "arthritis" (2M), or "cramps in shoulders and colds" (4G). Several limited air conditioner use due to comfort: "the air blowing", "the cold", or most explicitly, "with the air conditioner at work I get cramps, I get dizzy" (4G). Three mentioned safety; one never left it on when out of the room noting that the extension cord was hot to the touch, another more generally expressed a fear of electrical appliances being on when they were away from home (1B) and a third said they didn't leave electrical appliances on at night (2M). As mentioned previously, a disincentive to air conditioner use particular to this building was reluctance to turn it on for fear of blowing a fuse (4G, 1B, 4C).

Many residents expressed a sense that, even if one were not paying, it was incorrect or wanton to use the air conditioner excessively. For example, one said that she had gotten into the habit of using the air conditioner frugally when she had to pay, and she now continues her same usage patterns "[after] all those years of having a home and having to pay an electric and gas bill, I have an attitude that I'll only use it when I need it" (2M). Five of the eight expressed some form of disapproval of others who used the air conditioner excessively saying things like: older people are "good" with air conditioning, whereas younger people operate it even when it's cold outside (2K), (3A), some people leave it on at night (4K), "I swear, there are people in the building that leave the air conditioner running all winter long" (4N), "I hear units on, on a day like today...I think my God, they're warm in there?...why don't they crack some windows and turn on the fan?" (4C). Sometimes such comparisons were implicit in statements like "I'm not a heavy air conditioning user" (2M), and many were linked to folk physiological theories as seen in explanations such as "I'm older, less blood to keep cool" (3A), or "I am a warm person, maybe I'm a little anemic", "I can endure heat" (4J), or "other people need cooling more than I do because of their 'body chemistry'" (4G).

Like Hackett and Lutzenheiser (personal communication), we find that while only a few people use air conditioners at grossly inappropriate times, most residents seem to know about these few. On cool days well outside of the cooling season, we walked around the building several times and we would typically find one or two air conditioners running on each face of the building. The few we could get close to were running the fan only, but to the casual observer this sounds like the air conditioner is on. Many residents reported hearing air conditioners running when it was cool out and even could identify regular offenders, not by name but by location relative to a door or a stairway they used regularly. Hackett describes such inappropriate users as damaging the "social contract." Such a reaction could be seen if statements were made in an interview like "if they're so far out of line, I should at least be comfortable when I want." Our data provide no evidence for such a strong reaction, but we do find that just a few deviants lead many respondents to say that "some people" use the air conditioner a lot more than the respondent.

SCHEDULE EFFECTS

We next discuss the effects of daily schedule. Although the environmental variables have a built-in periodicity of 24 hours, a stronger diurnal effect results from people's daily schedules. Daily schedule effects were suggested in the interviews and are substantiated by the instrument data showing the air conditioners being switched on and off like an appliance. This operation contrasts with a central heating system in winter which is typically thermostatically controlled.

Figure 8 shows hours of air conditioner use as a function of time of day, broken down by weekdays and weekends. Here total hours of use are counted, not just compressor runtime, since our scheduling analysis concerns when the occupant turns the device on or off. The same three apartments are shown as on Figure 6, 2K, 2M, and 4J; these three span high, medium and low usage. Apartment 2K, the highest user, leaves the unit switched on at all hours of the day. Apartment 2M is strongly patterned by daily schedule, with weekday usage concentrated after work, and weekend usage more spread out; in neither case does she use it at night. Apartment 4J, which uses it very few hours altogether, uses it for brief periods after work and before going to bed, not at all on weekends.

We gain further insight into schedule effects by studying on and off events. We define an "on event"

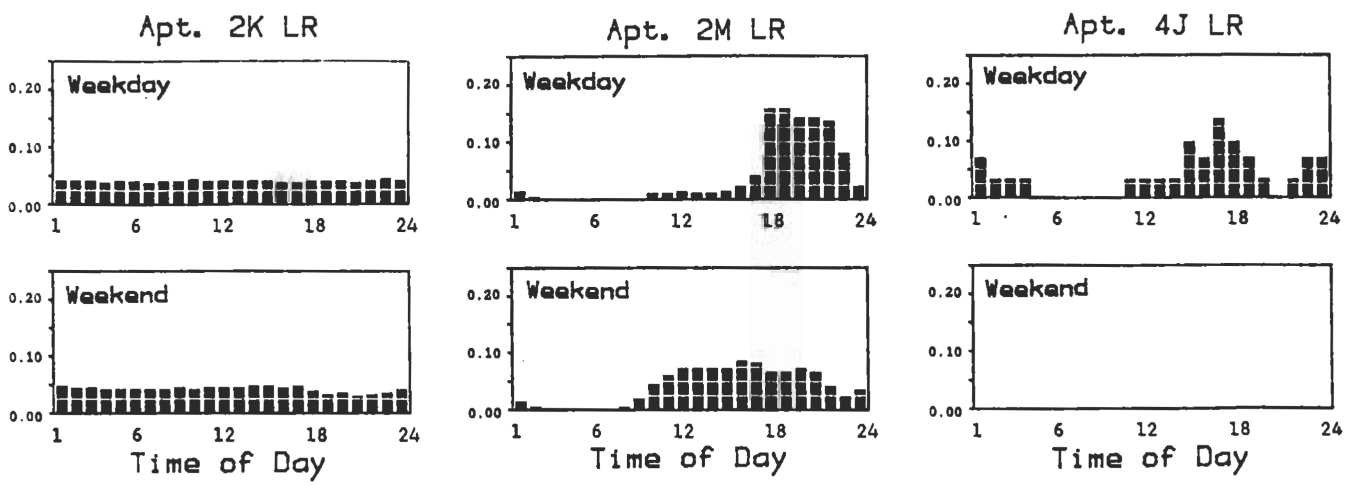

Figure 8. Air conditioner hours in use by time of day. Apartments 2K, 2M, and 4J are shown.

as measured operation following a period when the unit has been off for at least one hour. An "off event" is one where the air conditioner has been on during all or part of an hour and completely off for a subsequent complete hour. This method allowed us to approximate the user's behavior--switching the unit on and off--even though we had records of only compressor runtime. It is not as accurate for the few units which were run thermostatically, since the thermostat sometimes switched the compressor off for more than an hour.

For every apartment we grouped on and off events by hour of the day, distinguishing weekdays from weekends. Figure 9 illustrates 2M, one of the more well-patterned examples. A well-defined weekday peak can be seen for on events at or around 6pm, when the occupant returns from work. Off events are distributed from 6 through 12 pm. On weekends, the most common pattern is to turn the unit on between 8 and 12 am, and turn it off either at 3 or 4 pm, or more typically, after 6 pm. By contrast 2K was usually home during the day, and his graph (not included here) showed an almost randomly distributed pattern of on and off events.

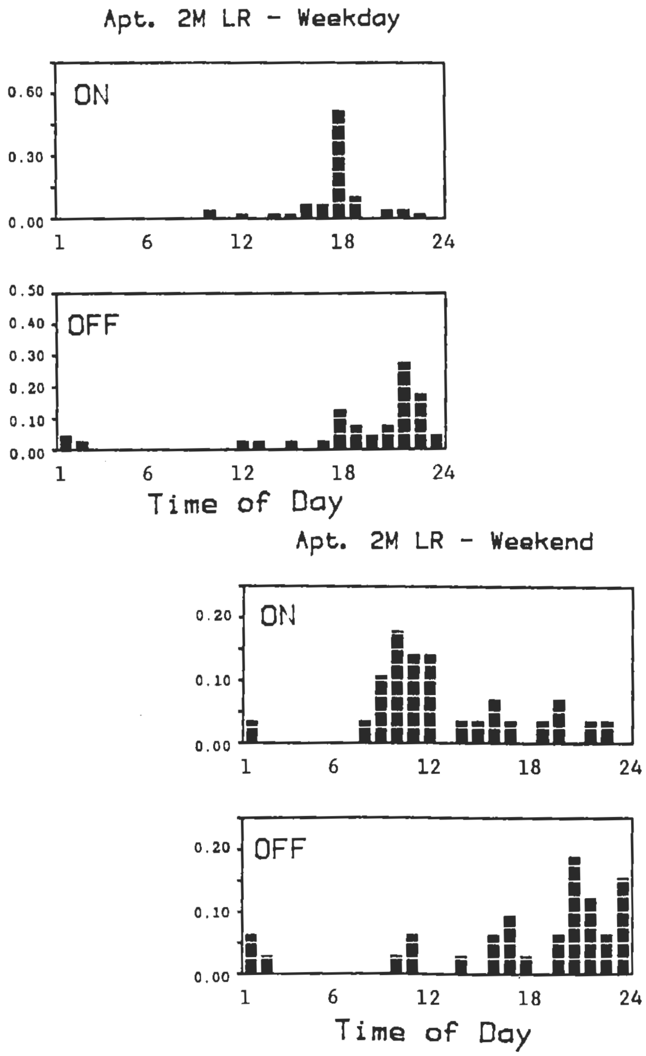

Figure 9. On and off events for the living room unit in apartment 2M, about 42 weekday events, 30 weekend events. Note that the weekday scale was expanded to accommodate the high weekday peaks.

SUMMARY AND CONCLUSIONS

A number of previous studies have acknowledged that behavior or lifestyle are important in air conditioning energy use, without going into much detail as to which "behaviors" or which "lifestyles" are the important determinants. In this study we have combined instrumented data from individual air conditioner units with interviews with the occupants, to produce a more complete picture of environmental and behavioral determinants of air conditioner use in this mid-Atlantic climate. We find in only one of the eight monitored apartments a clear and consistent thermostatic pattern. Two use it thermostatically for part of the time, while the remaining five turn it on and off like a simple manual applicance. Further, the majority did not understand that the air conditioner had a thermostat -- one even said he would like an automatic temperature-sensitive control like those on heating devices.

An improvement in the design of the controls of air conditioners may result in a change of user behavior. This is subject of ongoing research. Even in this building, where residents have no financial penalty for extensive use of the air conditioner, we found a wealth of non-economic reasons not to use it. Presumably these would be even stronger factors in dwellings in which energy was billed. We surmise that if not for these multiple non-economic determinants, air conditioner use would be dramatically higher than it is today.

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NOTES

1. Latent load and COP could introduce nonlinearities, but they have smaller effects in this range of temperature and humidity. See Brunello and Sonderegger (1985) for a thorough analysis of the relative effects of these factors.

2. Instrumentation was installed in an earlier set of apartments for a study of heating, selecting apartments believed to have heating problems (mainly on the top floor). For the present cooling study, already-instrumented apartments were retained, and our choice of additional apartments attempted to balance locations in the building and selected tenants who the manager suggested would be more willing to participate. We paid $50 to compensate for the inconvenience of sensor installation and maintenance.

3. Three orders of magnitude if comparing all air conditioning units, only two orders of magnitude if comparing living room unit.

4. The proportion seems larger than for heating, where Kempton (1987) estimates 25% to 50% have all or part of a valve model.